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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Recent studies on 27-day recurrence geomagnetic disturbances and their associated phenomena during the decline phase of the present sunspot cycle are summarized. An identification of M-region with solar phenomena has been made by evaluating the velocity of solar winds. Discussions are given on various existing hypotheses of corpuscular streams producing M-disturbances.

*Presented at the Inter-Union Commission on Solar Terrestrial Relations, Hamburg, Germany, August 24, 1964.

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INTRODUCTION

The sun is the source of major disturbances in the terrestrial upper atmosphere through its radiative and corpuscular emissions. Solar corpuscular emissions consist of three types, viz., energetic solar particles and plasma clouds associated with solar flares, and the outward streaming of solar winds or beams of enhanced activity originating from the solar corona. The flare-associated solar particles have been investigated extensively during the past IGY and IGC, and their results were discussed elsewhere (Reference 1). Meanwhile, successful launchings of deep space probes have led to the discovery of the continual flow of solar plasmas with velocities of some hundreds km/sec (Reference 2).

Renewed interest has arisen on the nature of recurrent geomagnetic disturbances with the solar rotation cycle, which had originally been suggested by Bartels many years ago as an enhanced stream of solar plasma ejected from some hypothetical active center of the sun, the so-called M-region. It has been known since the early part of this century that moderate geomagnetic disturbances show a tendency to recur at regular intervals of 27 days, particularly during periods of declining sunspot activity. Numerous investigations (Reference 3) have been carried out to identify the active region of the sun responsible for such disturbances. Bartels (Reference 4) first investigated the relation between recurrent geomagnetic disturbances and visible solar phenomena. No significant correlation was found. However, he noted that M-regions often occurred when the visible solar hemisphere was bare of sunspots or they tended to be absent when spots were near the central meridian of the sun. This feature was re-examined by Allen (Reference 5) and he has

*Presented at the Inter-Union Commission on Solar Terrestrial Relations, Hamburg, Germany, August 24, 1964.

†In order to provide a forum for discussion of the latest results on solar-geophysical disturbances during the period of quiet solar activity, a symposium on solar terrestrial relations was held on June 19, 1964, in Tokyo. A number of formal presentations were given and they were accompanied by much stimulating discussion. Following are the major topics and contributors:

1. 27-day Recurrence Disturbances in Geophysics
T. Saito, K. Nagashima, S. Mori, H. Ueno, and S. Sagisaka
2. On the Nature of Solar Winds
Y. Sano, T. Ondho, Y. Hakura, and A. Nishida
3. Identification of the Solar M-region
T. Goh, K. Sinno, S. Nagasawa, Y. Nakagomi, and Y. Nojima
4. Model of Solar Corpuscular Streams
(discussion lead by T. Obayashi)

The present article constitutes a summarized report of the symposium, including some introductory remarks on the background of the present problem in solar terrestrial physics.

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concluded that sunspots tend to interfere with M-regions, or in other words, the M-region apparently shows a tendency to avoid spot areas, which is known as the cone of avoidance hypothesis. This interesting feature has been confirmed in the relation between coronal emission-line intensity and geomagnetic disturbances. The first suggestion of this line of investigation was made by Waldmeier (Reference 6) who named the active coronal emission area as the C-region. Many investigators then showed that a significant minimum in geomagnetic activity follows 2-3 days after central meridian passage (cmp) of a region of active coronal emission, while two maxima in geomagnetic activity appear about 4-8 days after and also somewhat earlier than the time of the cmp of an active region (References 7 to 13). Similar conclusions have also been obtained by the superposed epoch method, using solar flocculi data for a 35-year period (Reference 14).

In contrast to the concept of the cone of avoidance, Mustel (References 15 and 16) advocated that M-regions appear to be correlated with active centers of the sun, possibly young plage regions, above which long coronal R-rays extend up to the distance of the earth's orbit. The coronal R-ray is believed to be a plasma stream, being composed of an assembly of radial magnetic field threads. There is another suggestion that M-regions are long-lived stable prominences, which are supposed to be remnants of old active regions.

In spite of these different hypotheses, all theories postulate solar active centers, and they admit that enhanced beams of solar corpuscles are the cause of recurrent geomagnetic disturbances. The important key to resolving the problem is, therefore, to determine the travel-time or the speed of streaming solar particles. Recent space probe data now provide this information. In their analysis of Mariner 2 plasma measurements, Snyder, Neugebauer and Rao (Reference 17) have shown that a strong 27-day recurrence tendency exists in the daily time sequence of solar plasma velocity and concluded that the solar M-regions must be the source of high velocity plasma. The average plasma velocity is nearly proportional to the geomagnetic activity or the daily sum of geomagnetic Kp indices. The estimated velocity of solar beams, thus derived from their results as well as the Explorer 18 data (Reference 18) ranges from 300 to 600 km/sec during the declining period of solar activity. This plasma velocity corresponds to the travel-time between the Sun and the earth of about 3 to 6 days, and the judgement of any theory must take into account this time-delay for solar-terrestrial relations.

There are some other phenomena which might be closely related to Solar M-regions. Cosmic ray variations, in particular, the diurnal anisotropy of the intensity, reveal a strong 27-day recurrence (Reference 19). As will be shown, a significant correlation exists between the phase change of cosmic ray diurnal variations and the enhanced S-component of solar radio emissions. The activity index of geomagnetic micropulsations reveals a clear 27-day recurrence. Recent investigation shows that this new measure of geomagnetic activity may be very useful to study the M-region disturbances (Reference 20). Since these phenomena are rather new and good data for the analysis are available only for the present cycle of the sunspot minimum, renewed studies on all related phenomena to solar M-regions during the present sunspot minimum will be discussed in what follows.

27-DAY RECURRENCE DISTURBANCES

In the present declining period of solar activity, some prominent recurrent geomagnetic disturbances have been observed. In Figure 1, a 27-day recurrence pattern of geomagnetic planetary index Kp is shown for the period from January to December 1963. Throughout the whole period, a persistent major peak of activity appeared between the 5th to 10th days in 27-day rotation

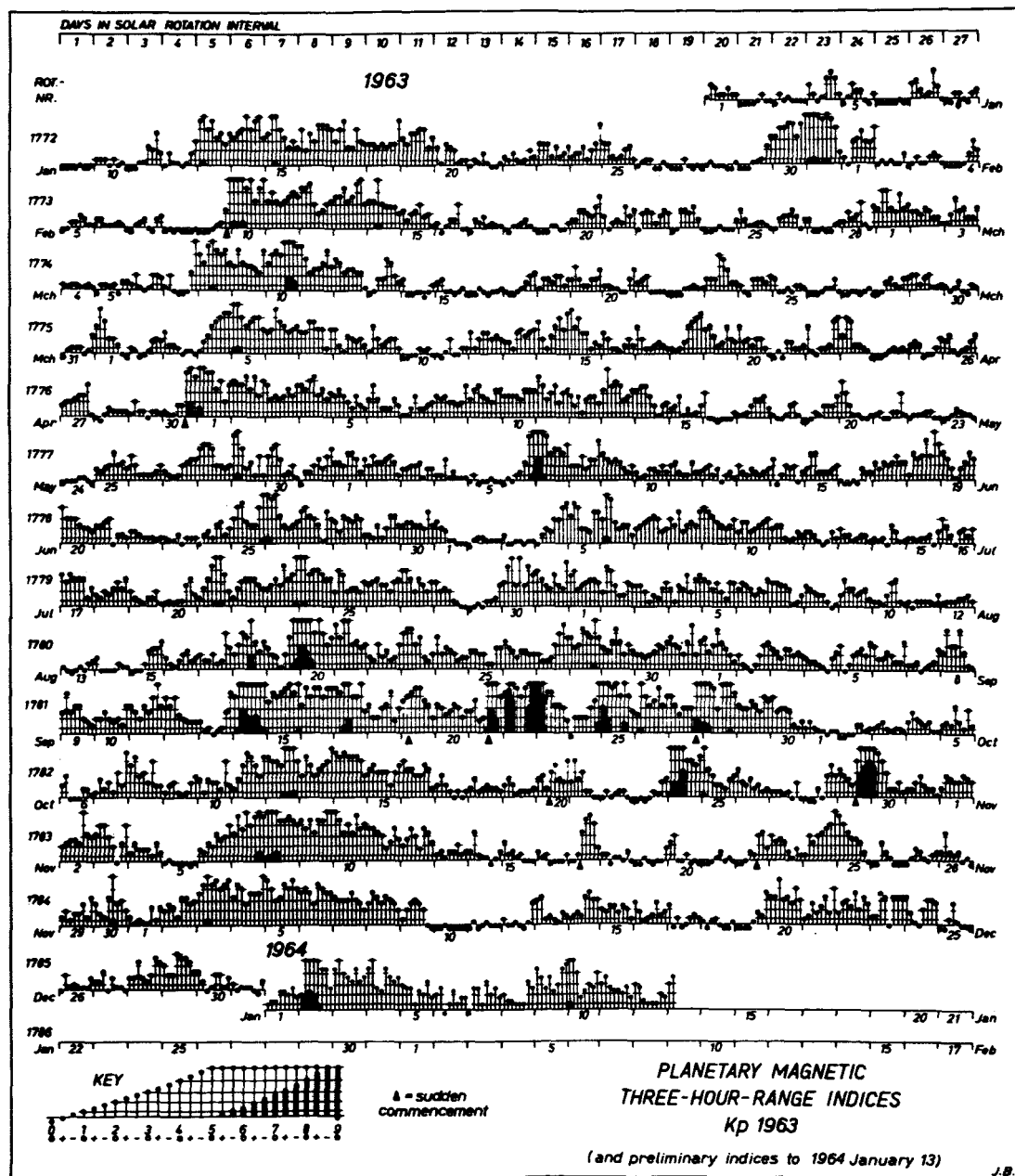


Figure 1—The 27-day recurrence pattern of geomagnetic planetary indices Kp from January to December 1963.

intervals. There were also short-lived minor peaks in the late half of the interval. Saito (Reference 20) has found that the activity of pc 3 geomagnetic pulsations reveals a very marked 27-day recurrence tendency in the same epoch. The daily cosmic ray intensity also showed a prolonged depression associated with the major peak of geomagnetic activity. For the corresponding solar activity, two bright coronal regions appeared in each rotation cycle. In the present period of analysis, the feature of such double maxima of activity seems to be common for all other solar phenomena, such as sunspots, calcium-plages, and solar radio emission (Reference 21).

Average 27-day variations of these solar and geophysical phenomena during the period of most pronounced 27-day recurrency, between numbers 1770 to 1776 are illustrated in Figure 2. As has been stated, a major peak of geomagnetic activity dates from the 5th to 10th days, being followed by the decrease of cosmic ray intensity. Coronal intensity and numbers of calcium-plages show double maxima, suggesting the existence of two stable centers of activity. It has

been shown that the slowly varying part, the S-component, of solar radio flux at microwave band recurs very regularly with peaks on the days of the 7th to 8th and near the 20th in each rotation cycle (References 19 and 22).

There is another interesting phenomenon, recurring with the 27-day interval, viz., the amplitude and phase of the diurnal variation of cosmic ray intensity, the so-called DS-component of cosmic ray intensity. Using data of meson monitor, Mori's group (Reference 19) obtained the average 27-day variation of cosmic ray diurnal vectors. It has been found that significant phase advancements occur at the 6th and 22nd days, which have been known to appear during cosmic ray storms. The 27-day inequality of cosmic ray DS, the varying part of diurnal vectors with respect to the solar rotation, has been reduced, by subtracting the mean DS of the whole 27-day interval. With an appropriate phase correction for the geomagnetic effect, these residual DS flow vectors denoted by ΔDS , are obtained. They are illustrated by arrows in Figure 3, on the heliocentric diagram together with average ΣKp and G6 variations. Although the physical mechanism causing the cosmic ray

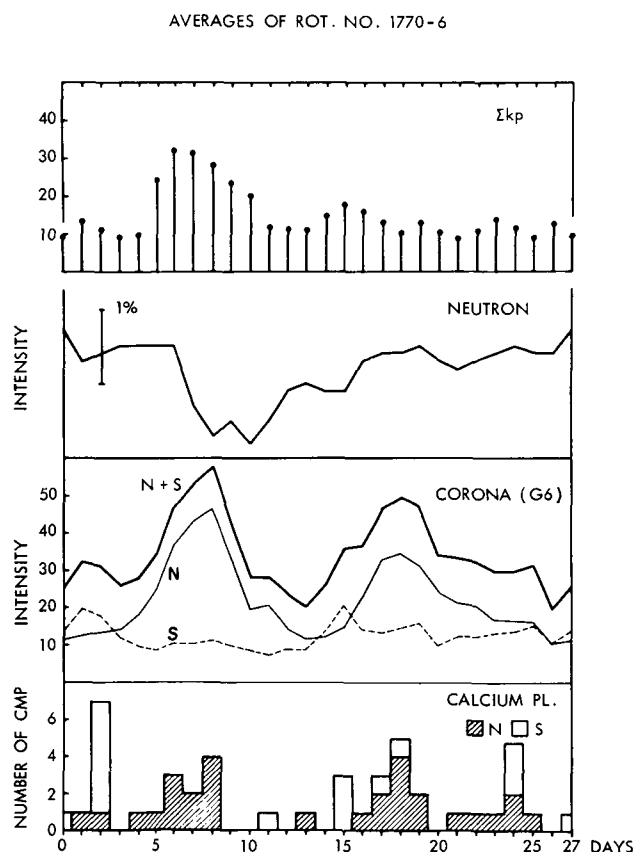


Figure 2—Average 27-day variations of geomagnetic index ΣKp , cosmic ray intensity (climax), coronal green line G6, and numbers of cmp of major calcium-plages during the period from November 1962 to May 1963 (Reference 23).

anisotropy has not been well understood, the ΔDS may indicate some additional flows, superposed upon the general modulation effect due to the outward streaming of solar winds. The regions of an excess of the outward flow are indicated by arc lines.

IDENTIFICATION OF SOLAR M-REGIONS

The general feature, illustrated in Figure 3, is the observational basis for the identification of hypothetical solar M-regions, responsible for recurrent geophysical disturbances. It is important to note that the time of peaks of geomagnetic activity appears a few days ahead of the cmp of solar active centers. Since we believe that geomagnetic disturbances are produced by particle streams from the sun, these active centers cannot be satisfactorily identified as the sources for the immediately corresponding peaks of geomagnetic activity. Furthermore, it is now known that the average velocity of plasma streaming out from the sun is about 400 - 600 km/sec, and these values yield the time-delay of the geophysical effect of 3 - 5 days.

To examine this point more quantitatively, the velocity of solar streams has been estimated from the value of ΣKp , by applying the Snyder's empirical relation between the solar wind velocity and ΣKp (Reference 17). The delay-time computed from the estimated velocity is, then, used to shift the time of geophysical phenomena, so that they may be compared directly with positions of solar active centers. The result is shown in Figure 4, in which the time of ΣKp and ΔDS is shifted approximately 3 - 5 days depending on their estimated stream velocities.

One of the features, which is immediately obvious, is that the major peaks of geomagnetic activity do not coincide with the center of coronal activity. The M-region should be located, if any, at the somewhat outer fringes of the active center, particularly, at the western side of the center. However, the situation is not so clear for other minor peaks of geomagnetic activity. A further discussion of the nature of solar M-regions is given later.

In earlier studies of the identification of solar M-regions, most investigators employed the superposed epoch method. For the present period November 1962 - May 1963, Sinno (Reference 23) made such an analysis and obtained the following result: a set of the superposed epoch graph of

AVERAGE 27-DAY PATTERNS DURING ROT. NO. 1770-6

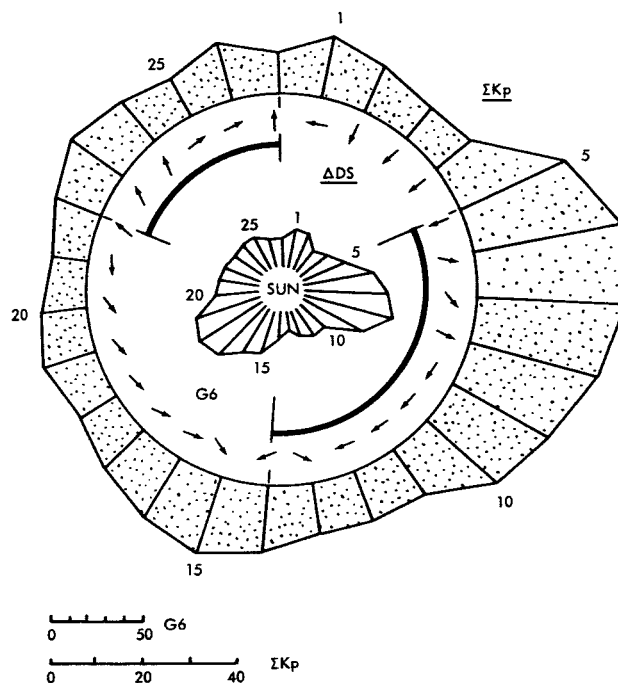


Figure 3—Heliocentric diagram of 27-day variations of coronal activity G6, cosmic ray ΔDS flow vectors and geomagnetic index ΣKp for the period of November 1962 to May 1963.

ΣKp for the cmp of bright and weak regions of solar corona, shown in Figure 5, exhibit somewhat different features compared with those of previous sunspot cycles. However, the general tendency revealed in the graphs seems to agree with the hypotheses of the cone of avoidance, because a minimum of ΣKp appears 3 to 5 days after the cmp of bright corona, and a maximum of ΣKp appears 2 to 8 days after the cmp of weak corona. A similar conclusion has been obtained by Nojima (Reference 21) for the relation between active calcium-plages and geomagnetic activity. For the sake of comparison, superposed epoch graphs which have been obtained for the earlier sunspot cycles are also reproduced in Figure 6 (References 12, 13 and 23). Since these analyses are statistical in nature, it is possible to have an apparent correlation between solar and geophysical activity even without any physical connection between them, provided that both of the time series have a 27-day periodicity. However, the similarity of patterns demonstrated here for the different epochs may be an important indicator of the likelihood that the above-mentioned relationship is real.

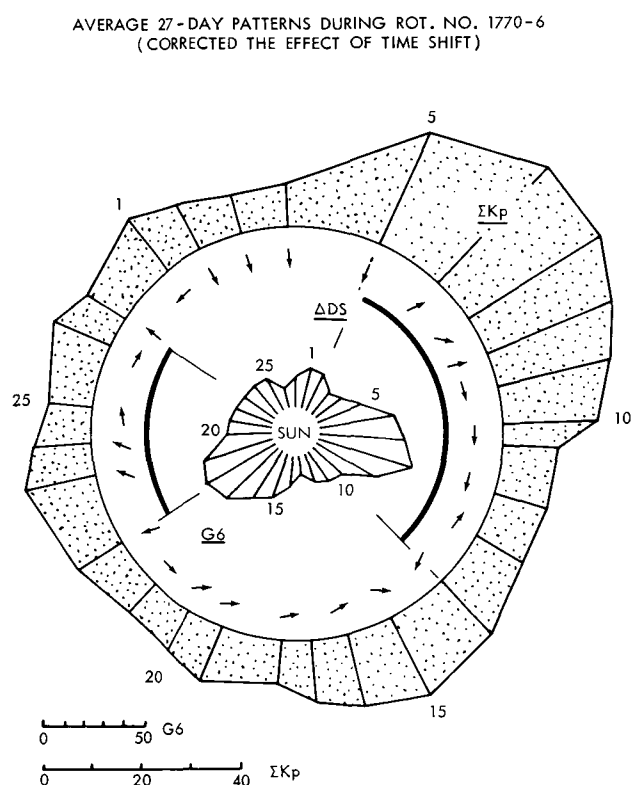


Figure 4—Heliocentric diagram of 27-day variations of coronal activity G6, cosmic ray ΔDS and geomagnetic index ΣKp . The time series of ΔDS and ΣKp are shifted according to the time-delay of geophysical effects estimated from the solar stream velocities.

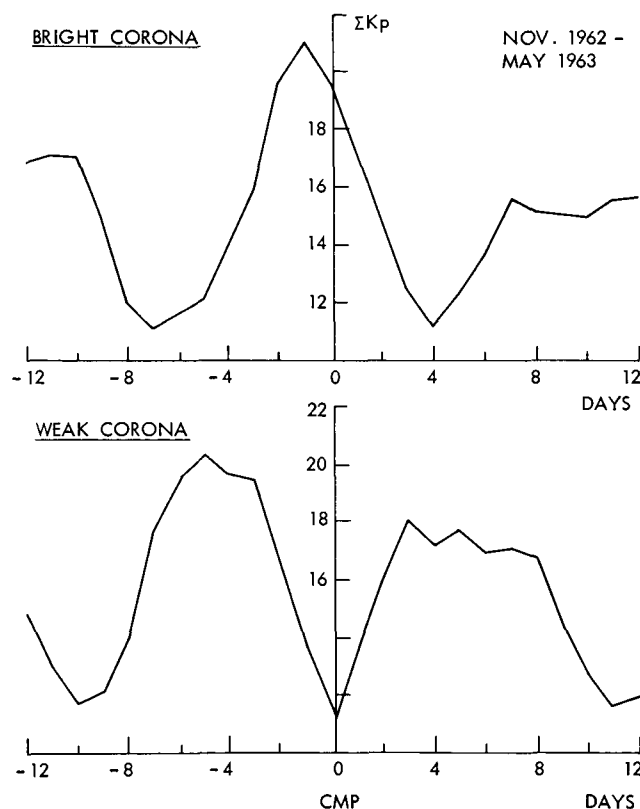


Figure 5—Superposed epoch graphs of geomagnetic activity for the cmp of regions of bright and weak coronal intensities for the period November 1962 to May 1963 (3 days running average, Rotation number 1770 - 1776) (Reference 23).

THE ANNUAL EFFECT OF M-REGIONS

Since both recurrent geomagnetic disturbances and coronal active regions often persist for many solar rotation cycles, their long-term variations have been investigated by several workers.

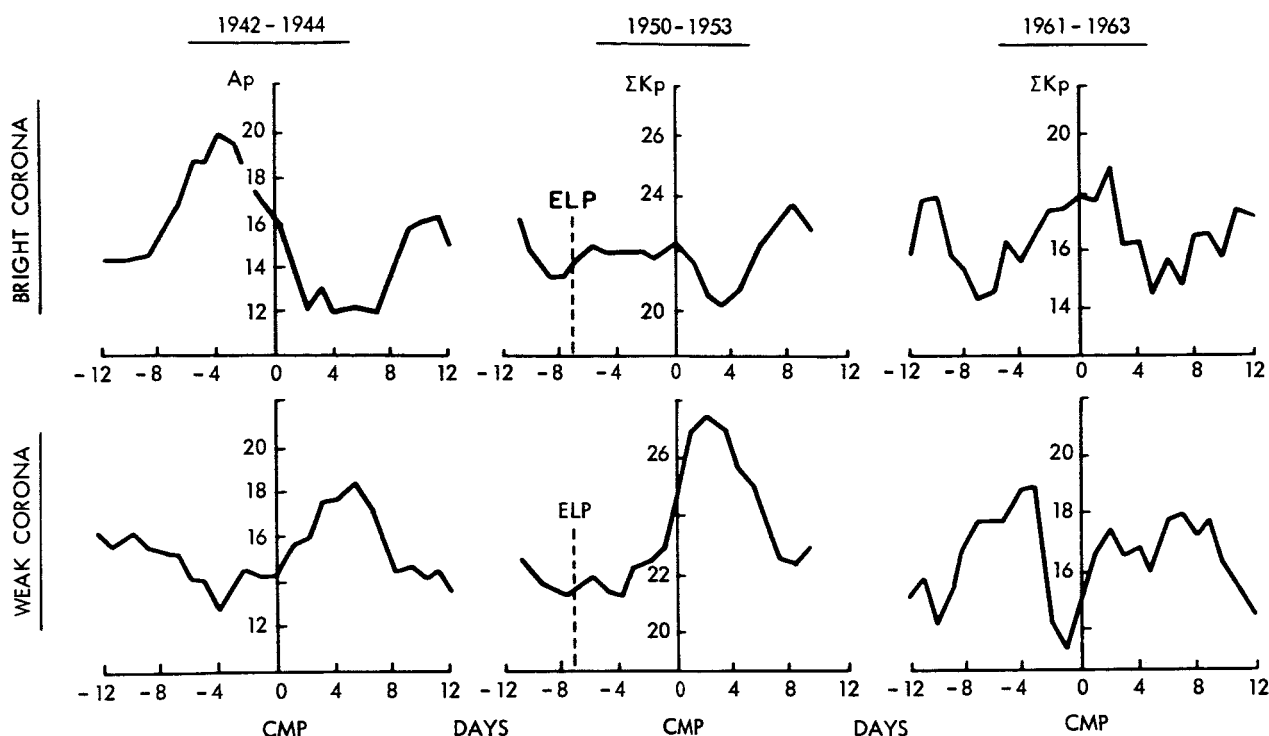
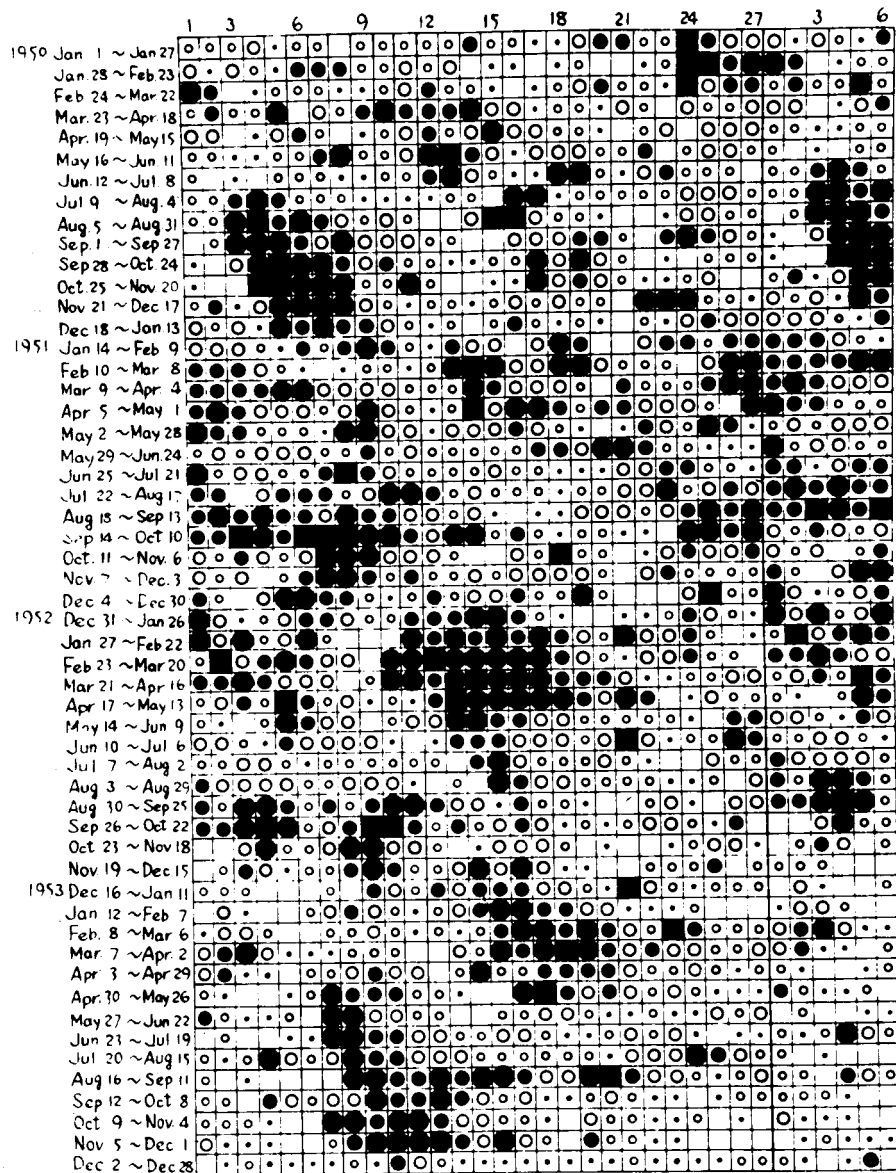


Figure 6—Superposed epoch graphs of geomagnetic activity A_p (or ΣK_p) after the cmp (or the eastern limb passage, elp) of bright and weak coronal regions, for the periods 1942 - 1944 (Reference 13), 1950 - 1953 (Reference 12) and 1961 - 1963 (Reference 23).

Sinno (Reference 11) has pointed out two very long sequences of M-regions in the period 1950 - 1954, each of which appears to show an annual variation. As shown in Figure 7, one long sequence located on the 3rd to 9th days of the rotation period showed a maximum activity around the autumnal equinox (September) and a minimum activity around the vernal equinox (March), which has been persisting for about three years or more. The other sequence appeared on the 12th to 18th days with its maximum around the vernal equinox. Such long-lived M-regions, being modulated by the annual period, have been found in the declining phase of every sunspot cycle (Reference 24).

The importance of this annual variation is that the beam from M-regions could be located not only on heliographic longitudes but also on latitudes, by taking into account the effect of the inclination of the solar axis to the plane of the ecliptic. It has been concluded by Bell and Glazer (Reference 12) that the solar active regions on the same side of the solar equator as the earth have a greater influence on geomagnetic activity than do the active regions on the opposite side of the solar equator. In other words, the efficiency of an M-region in producing geomagnetic disturbances appears greatest when the earth is around its maximum favorable heliographic latitude, viz., the southern hemisphere in the vernal equinox and the northern hemisphere in the autumnal equinox, while it appears least when the earth is near its unfavorable (the opposite side of the equator) heliographic latitude.



MAGNETIC ACTIVITY INTERNATIONAL CHARACTER-FIGURES



Figure 7—Twenty seven-day recurrence pattern for geomagnetic character figure, C-index for the period 1950 - 1953 (Reference 11).

From these observed facts of the directivity of solar streams from the M-region, Sinno (Reference 11) has been able to deduce the beam width of streams to be of the order of 10° in the solar meridian plane. This may be considerably narrower than the beam width in the equatorial plane, which is estimated to be of the order of 45° . Priestster and Cattani (Reference 25) found a similar beam width in the declining phases of sunspot cycle, from their analysis of the semi-annual variation of geomagnetic activity.

NATURE OF SOLAR M-REGIONS

An important conclusion derived from statistical analyses is that recurrent geomagnetic disturbances are produced by corpuscular streams (hypothetical) originating not from the center of solar activity but apparently from the outer fringes of the active area. According to the hypothesis of the cone of avoidance, an active center of the sun tends to inhibit the escape of corpuscles, and this is interpreted by assuming that solar particles are confined by strong local magnetic fields in the active center. In years of high solar activity, these trapped particles may be built up to form a strong condensation, being heated up further until they are finally exploded out. These are identified as solar flare corpuscles or flare-associated geomagnetic storms. In contrast to this explosive phase of solar activity, M-regions are such that the local magnetic fields are conducive to guide the continual outflow of corpuscular streams. This region may be compared to an unipolar magnetic region (Reference 26) where the outward stream is strong enough so that the magnetic field lines will be stretched out in the direction of the stream.

Thus, the hypothesis of the cone of avoidance has an attractive feature for explaining the peculiar inhibition of the corpuscular beam emerging from the active center. Nevertheless, this hypothesis itself cannot offer any positive mechanism for ejecting narrow and strong corpuscular beams from M-regions. On the other hand, it has been established that recurrent geomagnetic disturbances are closely related to the high velocity beam of solar winds (Reference 17). According to Parker's theory (Reference 27) the velocity of solar winds is very sensitive to the coronal temperature and, therefore, the solar corpuscular beam responsible for geomagnetic disturbances must originate from a high temperature region such as an active coronal condensation. As has been shown, however, this argument is not always consistent with observed results. Though Mustel's R-rays may be important for some recurring phenomena, they would possibly be remnants of solar flares, being dominated only during the stage immediately after the maximum solar activity (Reference 28).

An alternative hypothesis for the cause of recurrent disturbances has recently been proposed by Dessler and Fejer (Reference 29). Although they also postulate a high velocity beam streaming out from the active center, the origin of geomagnetic disturbances is attributed to a source other than the high velocity beam itself. It is emphasized that an enhanced solar stream alone cannot produce geomagnetic disturbances or high Kp, since the solar winds appear to be essentially ever-existing even during very quiet geomagnetic conditions. In these circumstances, they rejected the conventional view of the cause of the disturbances and proposed a hypothesis that

recurrent geomagnetic disturbances must be due to sheets of turbulence or irregularities that are generated at the interface of two solar wind regions of different stream velocities. The high velocity solar stream will overtake the lower velocity stream, and the collision of these streams would lead to the Kelvin-Helmholtz instability or the formation of two shock waves. This mechanism predicts the region of disturbances to lie westward of the high velocity beam originating from the active center, which turns out to be very consistent with the observed result shown in Figure 5 for the period 1962 - 1963.

As has been pointed out by Piddington (Reference 30) however, the Dessler-Fejer theory does not appear satisfactory with the result for the period 1950 - 1953, unless the stream velocity above the active region would generally be lower than that of the surrounding. For this case the M-region lies eastward of the active region of the corona, and he rather presumes that main disturbances originate at the region of the following side (eastward) of the high velocity beam, where the interplanetary field may be very weak or else lies in some favorable direction due to the sweeping action of a high velocity stream ahead of the region. A mechanism similar to this has been suggested, independently, by Sarabhai (Reference 31) as the source of recurrent cosmic ray storms.

CONCLUSION

At present, since there is no sufficient direct observation of solar streams to locate the M-regions, the conclusion derived from statistical analyses alone is necessarily speculative, and it cannot be well justified to accept or reject any one of the hypotheses discussed here. It is hoped that extensive observations made during the IQSY will provide much useful material, stimulating new approaches to understanding to mechanism of the solar M-regions.

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